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THE DISTRIBUTION OF ORGANIC CARBON AND NITROGEN IN SEDIMENTS FROM THE ARABIAN SEA

BY

JOHN D. H. WISEMAN, M.A., PH.D.

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WITH TWO TEXT-FIGURES

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I. INTRODUCTION.

Comparatively little work has been done on the organic content of marine sediments, and few attempts have been made to correlate the results with the productivity of the sea measured by actual plankton hauls or derived from chemical studies. Although much work has been done on soluble nutrients, little is known about the organic content of marine sediments—a situation which is difficult to understand, since the regeneration of organic matter in the sea-bottom is of special importance to those who are interested in the nitrogen cycle, and to the ecologist the question as to whether this organic matter is inert or is available as a nutrient for bottom fauna and bottom-inhabiting bacteria is a problem of special interest. In addition the oil geologist is interested in the potentiality of recent sediments as source beds, and in general it would seem likely that the more organic matter such a sediment contains the more likely it is to be a source bed. The hydrographical and hydrological conditions suitable for the deposition of sediments rich in organic matter are of interest to the geologist, as he hopes by a study of these to obtain a clearer picture of the conditions under which oil-bearing strata were laid down. It is therefore the primary object of this report to record the chemical estimations of carbon and nitrogen determined on sediments from the Arabian Sea, largely collected by the John Murray Expedition, 1933–34, and then to attempt the interpretation of these results. It must, however, be emphasized that this work should be regarded as preliminary owing to the stations being far apart, and the impracticability (this investigation was only a part of a more detailed chemical study subsequently to be published) of checking the conclusion by studying sediments from other oceans. It is to be hoped that future expeditions studying the productivity of the oceans will not ignore the information which may be obtained from the sediments, and will collect bottom samples with all possible oceanographical data. By this means more useful results will be obtained, and these will undoubtedly be helpful in the interpretation of other problems.

In the following pages a brief historical survey will first be given, and then the description of the chemical methods and a record of the analyses; but before attempting a discussion of the results it will be necessary to explain the factors governing the productivity of the sea as a whole, and the conditions favourable to the formation of marine deposits rich in organic matter.

II. HISTORICAL SURVEY.

The information available from older investigations is largely based on determinations of loss on ignition, but since marine deposits contain considerable amounts of uncombined and crystal-lattice water as well as sea-salts and carbonates any determinations based on loss on ignition must lead to inaccurate results, even if due allowance is made for decomposed carbonates. One of the first investigators to realize this was Sir John Murray (1891), who considered that loss on ignition cannot entirely be attributed to organic matter; and with the object of determining the nature of organic matter, carbon and nitrogen were estimated in a Globigerina Ooze (Challenger Station 224, 1850 fathoms) from the West Pacific Ocean. The figures given are C 2·80%, N 0·785%, giving a very low C : N ratio of 3·6. Murray concluded that an albuminoid substance is present, whilst Von Gümbel (1888) suggested that the organic content was made up of both albuminoid and fatty substances. Gazert (1912) studied the sediments collected by the German South Polar Expedition, and stressed

the relation between the amount of organic matter and the number of organisms. The chemical estimations were done by Gebbing (1909), who determined the total loss on ignition and made corrections for the loss of carbon dioxide and sodium chloride. Values found varied from 0·7% to 4·5%, the latter occurring in a Red Clay.

Boysen Jensen (1911*a*) estimated carbon and nitrogen in several bottom samples from Danish waters, as well as in eight samples collected by the Ingolf Expedition. A sand from the North Sea contained on a dry basis (100° C.) 0·34% organic carbon, and 0·027% nitrogen. The carbon content of bottom samples from various parts of Liim Fjord varied from 0·58% to 4·3% with a C : N ratio of 8·1 to 12·4. The clay bottom of the Kattegat, at depths of 30 to 35 metres, contained 2·3% carbon, with a C : N ratio of 11·5, while the mud from Roskilde Fjord contained as much as 10·2% carbon. Boysen Jensen (1914), finding that planktonic matter contained 50% carbon, suggested the factor 2·0 for calculating the amount of organic matter from organic carbon, but the use of this factor implies that there is no decided change in the balance of the various chemical constituents during the transformation of plankton, algal material, and other marine forms of life into marine humus.

Moore (1930) estimated the organic matter in the muds of the Clyde Area by their nitrogen content, and investigated the variations with depth. In general there was a fall of nitrogen with increasing depth in the sediment, though at a few stations a rise was recorded. The fall of nitrogen, according to Moore, might be accounted for by the breaking down of the organic nitrogenous compounds into nitrates and nitrites, and the removal of these into the water above.

In a series of determinations of organic carbon content of marine sediments collected in the Channel Islands Region, California, Trask (1931*b*) reported that the organic carbon content ranges from 0·4% in a near shore sand to 4·2% in a clay at the bottom of the Santa Cruz basin, and he concluded that the organic content follows the bottom configuration, being high in the depressions and low on the ridges. In a more detailed communication Trask (1932*a*) has collected together carbon and nitrogen determinations on approximately 100 marine sediments from the Channel Islands area and other coastal regions, as well as giving the nitrogen content of many oceanic samples.

Waksman (1933*a*), studying the abundance and distribution of organic matter in marine sediments off the east coast of America, suggested that organic matter in marine sediments can be designated " marine humus ", thereby making it comparable to soil humus. The organic matter was calculated from the organic carbon content, which was determined by Tiurin's (1931) modification of Schollenberger's method. The nitrogen determinations were made by the Kjeldahl method. A series of mud samples taken from several stations in the Gulf of Maine shows little variation at each station when the samples are not taken too far apart, but when the samples are taken at greater distances the humus content shows considerable variations. Determination of the organic content in cores up to 112 cm. long showed in general a gradual but slow reduction with depth, but in one case there was an increase with depth. Only a few bottom cores at greater distances from shore were investigated; one taken by the " Nautilus " expedition north of Spitzbergen, and the others taken by the "Atlantis " on a cruise to Bermuda in September, 1932. The organic carbon content of the marine mud north of Spitzbergen is 0·85%, whilst four samples collected by the "Atlantis " varied between 0·35% and 0·46%.

Gripenberg (1934*a*) determined organic matter in a series of sediments from the North

Baltic. The organic carbon was determined by combustion *in vacuo*, the CO_2 evolved being absorbed by N/10 barium hydroxide. In order to obtain the organic content, Gripenberg multiplied the organic carbon percentage by the factor 1·724. The greatest deviation between two single analyses, according to the author, was 0·1%, corresponding to a deviation of approximately 0·05% in the organic carbon content. The nitrogen analyses on the Baltic samples were done by Wasastjerna, according to the micro-Kjeldahl method. Nitrogen determinations were considered good if they did not differ by more than 0·03% from each other. In the Baltic it was found that the late glacial and the post-glacial sediments form two distinct groups, the glacial sediments containing much less organic matter owing to excessive supply of inorganic detritus formed by the action of the ice sheets on the underlying bed rock. In addition Gripenberg investigated the variations of organic matter with depth, and found that down to depths reached by the sampler (about 20–35 cm.) late glacial clays had a fairly uniform organic content, but for the post-glacial sediments the analyses seem to indicate that the organic matter within the first 20 cm. of the bottom decreases with depth in the sediments of the Bay of Bothnia, but increases with depth elsewhere in the investigated area. It is suggested that this increase with depth is due to changed conditions of sedimentation.

Most extensive determinations of organic carbon were carried out by Correns (1935, 1937*a*) on the " Meteor " cores. In his report carbon determinations are recorded from 100 stations, situated in the equatorial regions of the Atlantic Ocean. In addition the variation of carbon in the deeper portions of the core samples was investigated, but unfortunately no nitrogen determinations are available on any of the " Meteor " samples. The " Meteor " results, although extensive and of great interest, are on this account of limited value. Carbon was estimated by oxidizing it to carbon dioxide by means of chromic acid, and absorbing the liberated carbon dioxide. The carbon dioxide content was, after making allowance for the carbon dioxide present as carbonates, multiplied by the factor 0·471 to obtain the organic content of the sediment. A relation was established between the organic matter and the carbonate content of the sediments, the average value falling with an increase of the carbonate content. It was concluded that approximately 0·2% of organic matter is present in the binding material of foraminiferal shells. No sediments of high humus content were collected by the expedition, the organic carbon contents being consistently below 1%. Correns found no relation between the humus content of a sediment and the amount of oxygen present in the water, but he considered that this may be due to the relatively few determinations of oxygen immediately above the sea-bottom, as well as the interfering nature of other factors. It is pointed out that in regions rich in sea life the deposits should be rich in humus, provided the conditions of sedimentation are suitable for the retention of humus, and such a relation between the plankton distribution and the humus content exists in the Cape Verde region.

The Scripps Institute of Oceanography has investigated the nitrogen content of marine sediments from the Californian region, but their results are not published apart from a preliminary report (Moberg, 1937). In this report it is stated that there is, in general, an increase in the amount of nitrogen with increasing depth and distance from the shore up to more than 100 miles from land, after which there is a decrease at greater distances. Analyses of core samples show that the highest nitrogen values are found at the surface of the sediments, and within a core sample 50 cm. long, the content at the lower end falls to about two-thirds that found near the surface.

III. ESTIMATION OF ORGANIC MATTER IN MARINE SEDIMENTS FROM ORGANIC CARBON CONTENT.

So far no direct means of determining accurately the organic content of marine sediments has yet been devised. Soil chemists estimate the organic content of the soil by multiplying the organic carbon content by a factor, and in spite of considerable disagreement, there seems to be a preference for the factor 1·724, corresponding to 58% carbon in soil organic matter. Although the formation of organic matter in soils depends on many factors, such as the activity of various micro-organisms, temperature, moisture and aeration, yet the final product is of fairly constant composition. It could be argued, however, with some justification that the factor 1·724 is inappropriate for marine deposits because of the marked difference in chemical composition between land and marine plants. Boysen Jensen suggested the factor 2, but as we have mentioned above, this assumes that there is no change in the balance of the various chemical constituents during decomposition. The organic matter of marine muds collecting not far from the shore is undoubtedly partially of terrestrial origin, and consequently one might reasonably expect this organic matter to have a ligno-protein nature with high carbon content. On the other hand the residues of marine plants, largely consisting of carbohydrates with low carbon content, should lower the carbon content of organic matter. Investigations have therefore been carried out by various authors to determine the nature of marine organic matter, but these unfortunately are not wholly satisfactory. Waksman (1933*b*) treated marine mud with a 4% solution of NaOH, and by this means 70% of organic matter was abstracted. The abstracted material was made up of the following complexes: lignin 21·0%, protein 30·2%, hemicelluloses, etc., 18·8%. From these results it was tentatively computed that the percentage of carbon in the abstracted organic matter is about 53. If the carbon content of marine organic matter is 53% the factor to be used for calculating the organic matter from organic carbon content is 1·887; but this assumes that the percentage of carbon in the remaining 30% is the same as that in the abstracted portion.

Trask (1931*a*) uses the factor 1·7, Correns (1937*b*) the factor 1·73, Gripenberg (1934*b*) the factor 1·724. In this report the latter factor has been adopted, not because the authors believe that the chemical composition of marine organic matter is the same as soil humus, but because they consider that there is insufficient chemical evidence about the nature of marine organic matter, especially that occurring in deep water, to warrant the use of a factor different from that used by soil chemists. In this report stress is laid on the organic carbon content and not on the humus content, as the humus content of marine sediments is at present largely hypothetical.

IV. CHEMICAL METHODS.

As carbon is the major constituent of organic matter it affords the most desirable means of measuring the organic content, but unfortunately in sediments containing carbonates organic carbon cannot be determined directly, but is the difference between total carbon and carbonate carbon. It has therefore been suggested by some authors that nitrogen forms a more practical means, especially since the method is simple, rapid, and accurate. Trask (1932*b*) has adopted this method for his investigations dealing with the source sediments of petroleum, and he considers that the C : N ratio is approximately constant and

equal to 8·4. Assuming that the organic matter is 1·724 times the organic carbon, it follows that the organic content is about 14·5 times the percentage of nitrogen. In our investigations this method was not adopted. The amount of nitrogen in organic matter is relatively small, and consequently the factor by which it has to be multiplied is large, and if the C : N ratio is not constant in sediments considerable errors will be introduced. The authors of this report believe that this ratio is more variable than has previously been suggested, and it will be shown on a subsequent page that in sediments from the Arabian Sea this ratio varies between 4·9 and 34·2. In the sample with the low ratio the organic matter calculated from organic carbon is 0·97%, and calculated from nitrogen 1·67%, whilst in the sample with the larger ratio, the organic matter is 1·95% or 0·48%, depending upon whether it is calculated from carbon or nitrogen. The error introduced by calculating organic matter from nitrogen content may, therefore, greatly exceed the possible error in the determination of organic carbon. Although it is probable that the percentage of organic carbon in organic matter is not constant, it is nevertheless great and presumably always over 50%. In our opinion, organic matter is more accurately determined from organic carbon.

As a disadvantage of determining organic matter from organic carbon, it may be urged that if the carbonate content is high, decomposition by combustion may not be complete. This difficulty can easily be overcome by determining total carbon by a wet method, as was adopted in this report, or possibly by removing the carbonates before combustion. Wahnschaffe and Schucht (1924) suggest the use of sulphurous acid for this purpose. Gripenberg (1934*b*) followed this method, and treated the weighed samples a few times on a water bath with small portions of saturated sulphur dioxide solution, after which they were transferred into the combustion boat. It was found that the sum of the carbon dioxide from the organic matter and the carbonates was smaller than that found by direct combustion analysis; in other words, organic matter was lost during treatment. Gripenberg concluded that on the average samples which have been subjected to preliminary treatment with sulphurous acid lose about 0·25% organic carbon.

In our investigations organic matter was determined from organic carbon not only because we regard it as a more accurate method than multiplying the nitrogen by a large and uncertain factor, but also because we desired to investigate the variations of the C : N ratio in marine sediments, and determine whether such possible variations could be correlated with any oceanographical features.

For the determination of organic carbon both wet and dry combustion methods were tried. In the wet combustion method a mixture of chromic acid and phosphoric acid was used as an oxidizing agent (Harwood, 1933), and for dry combustion the sample was mixed with lead chromate or copper oxide and ignited in a combustion tube. In both methods the carbon dioxide evolved was absorbed in soda lime and weighed. The results obtained by the combustion method were all slightly lower than those from the wet method, and this difference was traced to carbon dioxide retained by lead chromate. The same difficulty was experienced when lead chromate was replaced by copper oxide. Consequently it was decided that the wet method was the more suitable both on account of the retention of carbon dioxide, and the danger of the incomplete dissociation of the carbonates in the combustion method.

The apparatus employed consisted of a 250 c.cm. round-bottomed Pyrex flask, fitted with a tap funnel head with side outlet tube. The side tube was connected to an empty

U-tube in order to catch the water condensing during distillation, and the other arm of the U-tube was connected with an absorption train. This consisted of:

(1) A bubbler with phosphoric acid containing a little chromic acid.
(2) A tube containing pumice impregnated with anhydrous copper sulphate to absorb any hydrochloric acid not already caught.
(3) A calcium chloride tube.
(4) Two weighed soda lime tubes.
(5) A calcium chloride guard tube leading to the pump.

About ½ grm. of the sample was weighed out into the dry flask and 3 grm. of chromic acid added. The tap and stopper of the funnel were lubricated with a drop or two of phosphoric acid and the apparatus fitted together. Twenty c.cm. of phosphoric acid were run slowly into the flask from the funnel and the flask gently heated. When most of the carbon dioxide from the carbonate had been evolved the heat was gradually increased until the contents of the flask turned green and the heating was continued for thirty minutes longer. The whole operation took about two hours. The flame was then extinguished and air drawn through the apparatus for twenty minutes. The soda lime tubes were removed and weighed after standing half an hour in the balance case. The blank, using A.R. materials, was generally not more than 2 mgrm.

The carbon dioxide associated with the carbonates was determined by a similar method using phosphoric acid alone and a simplified form of the apparatus. The difference between the two values gives the carbon dioxide from the organic matter, from which the organic carbon content of the sediment was calculated.

The method described above is long, but needs little attention, and was found to give quite satisfactory duplicate results. It was found unnecessary with these samples to pass the gas through a heated solution of mercuric oxide in phosphoric acid, as recommended by Dixon (1934) in the case of certain rocks and minerals.

Some typical duplicate results on samples containing varying amounts of organic matter are shown in Table I below.

TABLE I.

Sample.	Organic carbon.	Difference.
170 Globigerina Ooze	0·55, 0·57	0·02
160 Cream Mud	1·10, 1·01	0·09
114 Brown Mud	1·51, 1·55	0·04
179 Green Mud	2·15, 2·11	0·04
180 ,,	2·93, 2·92	0·01
55 Brown-green Mud	5·17, 5·21	0·04

In the above typical results the organic carbon content as determined by duplicate analyses differ from each other in all but one case by a smaller percentage than 0·05. The authors consider that in general the organic carbon analyses recorded in this report have an accuracy of ± 0·05%. Trask (1932*b*) considered that the probable error of any individual organic carbon determination was about 0·2%, but the methods he adopted were different from those used in our investigations.

Gripenberg (1934*c*) has suggested that marine samples when heated at a low temperature may lose part of their organic matter, and it is therefore of some importance to know whether on drying the samples at 105° C. in order to determine H_2O-, any appreciable organic matter is lost. To test this idea three green muds which contained considerable organic matter, and also gave a high loss at 105° C., were chosen, and organic carbon determined before and after drying at 105° C. The results obtained are shown in Table II.

TABLE II.

Sample.	Loss at 105° C.	Organic carbon before drying.	Organic carbon after drying at 105° C.
55 Green Mud .	5·08	5·17 } 5·19	5·14 } 5·13
	5·08	5·21 }	5·12 }
66 ,, . .	4·12	4·73	4·78
56 ,, . .	3·48	3·57	3·49

In the above table the differences are within the limits of the experimental error of the carbon determinations, and these results would indicate that the loss of organic carbon at 105° C. has no appreciable effect on the accuracy of the H_2O- determination.

Nitrogen was determined in the samples by the micro-Kjeldahl method, and as the percentage of nitrogen is low, 0·2 grm. of the sample was weighed out on an ordinary balance, and the determination done in the usual micro-apparatus. Sodium selenate was used as a catalyst and N/100 hydrochloric acid and caustic soda for the final titrations. Determinations of nitrogen were made in duplicate and seldom differed by as much as $\pm$ 0·003%. In a few cases when the difference was more than this further determinations were made. Some typical results on samples of varying nitrogen content are shown in Table III.

TABLE III.

Sample.	Nitrogen.	Difference.
170 Globigerina Ooze .	0·024	0·003
	0·027	
160 Cream Mud . .	0·060	0·001
	0·061	
85 Grey Clay . .	0·125	0·001
	0·124	
33 Green Mud . .	0·293	0·006
	0·287	
21 ,, . .	0·327	0·002
	0·325	
55 ,, . .	0·506	0·003
	0·503	

V. ANALYTICAL RESULTS.

For purposes of convenience the analytical results are tabulated in Table IV, the Murray Expedition Stations being arranged in order of increasing depth. In addition

a few samples from the British Museum collections have been investigated. In the first column the station number is given, and in those cases where the lower portions of the cores have been investigated the average depth from the top is recorded. In the second column the depth is given, in the third the latitude and longitude, and in the fourth the amount of organic carbon. During this investigation it was found that the H_2O- content of the samples did not remain constant even when the sample was stored in a well-corked bottle. It was therefore decided, in order to make the analyses more comparable, to recalculate the organic carbon content on a H_2O- and NaCl free basis. The results of this recalculation are given in the fifth column, whilst in the sixth the organic carbon is given on a $CaCO_3$, H_2O-, and NaCl free basis. The seventh column represents the amount of organic matter in the original sample, whilst in the eighth the amount of nitrogen in the original sample is recorded. Nitrogen is recalculated without H_2O- and NaCl in column 9, and in the tenth without H_2O-, NaCl, and $CaCO_3$. In the eleventh column C : N ratio is given, and in the twelfth the $CaCO_3$ present in the original sample. The thirteenth column represents the CO_2 content recalculated without H_2O- and NaCl, whilst in the fourteenth column the CO_2 is recalculated without organic matter, H_2O-, and NaCl.

Samples from 44 different stations were investigated, and in the lower portions of the cores determinations were made at 16 stations.

VI. FACTORS GOVERNING THE PRODUCTION OF ORGANIC MATTER.

Before attempting the interpretation of the above results it is necessary to discuss the factors which govern the productivity of the sea as a whole, especially as mineralogists and geologists are not normally acquainted with this subject. Although the productivity of the sea is ultimately responsible for organic matter in recent sediments, as well as in marine deposits of past ages, it is desirable to mention, in addition, the factors which govern the regeneration of organic matter and the subsequent dispersal of the regenerated nutrients.

(*a*) The Nitrogen Cycle.

It is well known that the sea in its upper layers supports a rich flora, and the immensely varied animal population is entirely dependent either directly or indirectly upon the flora for carbohydrates and proteins. Some of these animals feed on marine algae during the whole or part of their lives, whilst others are carnivorous, preying upon their neighbours and ingesting and feeding upon particles of dead organisms and bacteria. It follows, therefore, that marine plants exert a most powerful influence on marine fauna.

The larger marine algæ are sessile and are confined to a comparatively narrow zone around the coasts, and the maximum depth at which they are found varies with the depth to which light penetrates in appreciable quantities. Besides the fixed algæ very numerous small plants, mostly unicellular, and known as phytoplankton, occur in the upper illuminated layers of the sea. The depth to which phytoplankton grow and multiply rarely exceeds 150 metres, and on death or during old age they sink slowly, often with the formation of spores. Phytoplankton may be devoured by zooplankton or decomposed

Table IV.

Station No.	Depth (metres).	Latitude.			Longitude.			Organic carbon.	Organic carbon on a H_2O–and NaCl free basis.	Organic carbon on a H_2O–, NaCl and $CaCO_3$ free basis.	Organic matter.	Nitrogen.	Nitrogen on a H_2O–and NaCl free basis.	Nitrogen on a H_2O–NaCl and $CaCO_3$ free basis.	C : N.	$CaCO_3$.	CO_2 on a H_2O– and NaCl free basis.	CO_2 on a H_2O–, NaCl and organic matter free basis.
		°	′	″	°	′	″											
160 . .	37	4	52	30 N.	72	51	36 E.	1·06	1·11	13·82	1·83	0·061	0·064	0·795	17·1	87·78	40·44	41·23
73 . .	91	25	28	48	56	35	54	0·88	0·90	3·87	1·52	0·070	0·071	0·308	12·6	75·58	33·80	34·34
164 . .	183	8	15	24	73	01	30	0·55	0·56	14·87	0·95	0·043	0·044	1·162	12·8	94·12	42·32	42·73
70 . .	196	25	34	12	57	23	30	1·69	1·79	2·15	2·91	0·144	0·153	0·183	11·7	15·60	7·28	7·51
75 . .	201	25	10	48	56	47	30	2·15	2·28	4·61	3·71	0·218	0·232	0·468	9·9	47·56	22·21	23·12
106 Top . .	212	5	38	54 S.	39	15	42	1·49	1·58	4·76	2·57	0·110	0·117	0·352	13·5	62·79	29·36	30·18
106 (32¼ cm.) .	212	5	38	54	39	15	42	1·52	1·65	4·95	2·62	0·112	0·121	0·365	13·6	61·59	29·34	30·20
106 (54½ cm.) .	212	5	38	54	39	15	42	1·38	1·48	4·65	2·38	0·100	0·108	0·337	13·8	63·33	29·93	30·73
206 . .	256	13	57	30 N.	42	35	24	2·12	2·26	6·80	3·65	0·157	0·168	0·504	13·5	62·50	29·34	30·54
191 . .	274	13	46	30	47	48	54	2·17	2·24	4·34	3·74	0·203	0·209	0·406	10·7	46·91	21·27	22·13
179 . .	275	12	02	06	50	40	12	2·13	2·21	18·06	3·67	0·201	0·209	1·704	10·6	84·43	38·59	40·13
114 . .	353	5	06	08 S.	59	14	05	1·53	1·63	3·85	2·64	0·131	0·139	0·330	11·7	54·41	25·40	26·14
180 . .	366	12	03	24 N.	50	40	12	2·93	3·09	16·24	5·05	0·260	0·274	1·441	11·3	76·85	35·60	37·61
207 . .	375	14	08	56	42	19	00	2·85	3·06	8·82	4·91	0·207	0·222	0·640	13·8	60·75	28·71	30·31
56 . .	421	22	12	42	59	51	18	3·57	3·92	6·73	6·16	0·293	0·322	0·552	12·2	37·93	18·33	19·65
64 . .	448	24	47	00	61	21	18	0·53	0·54	0·62	0·91	0·101	0·104	0·118	5·2	12·10	5·45	5·50
66 Top . .	609	23	44	24	58	40	00	4·73	5·35	8·26	8·16	0·382	0·432	0·667	12·4	31·11	15·48	17·06
66 (43 cm.) .	609	23	44	24	58	40	00	4·27	4·62	6·99	7·36	0·283	0·306	0·463	15·1	31·34	14·91	16·20
55 . .	794	22	07	30	59	52	12	5·19	5·79	7·92	8·95	0·505	0·564	0·770	10·3	24·06	11·80	13·11
117 . .	889	3	38	48 S.	40	23	42	1·87	2·03	4·28	3·22	0·127	0·138	0·290	14·7	48·51	23·13	23·96
65 . .	907	25	02	12 N.	59	40	30	3·28	3·49	4·09	5·65	0·292	0·310	0·364	11·2	13·96	6·53	6·94
20 Top . .	1132	11	54	12	45	16	30	4·43	4·76	10·55	7·64	0·346	0·372	0·824	12·8	51·00	24·12	26·28
20 (41¼ cm.) .	1132	11	54	12	45	16	30	2·39	2·51	6·79	4·12	0·158	0·166	0·449	15·1	59·91	27·70	28·96
119 Top . .	1204	6	29	24 S.	39	49	54	1·16	1·24	3·13	2·00	0·058	0·062	0·157	20·0	56·61	26·58	27·16
119 (31¼ cm.) .	1204	6	29	24	39	49	54	1·70	1·89	2·99	2·93	0·111	0·123	0·195	15·4	33·13	16·19	16·73
119 (66¾ cm.) .	1204	6	29	24	39	49	54	1·05	1·14	2·83	1·81	0·054	0·059	0·145	19·4	54·71	26·19	26·73
33 Top . .	1295	13	41	00 N.	48	17	00	3·17	3·34	6·80	5·47	0·290	0·306	0·622	10·9	48·22	22·37	23·73
33 (37½ cm.) .	1295	13	41	00	48	17	00	2·15	2·26	5·22	3·71	0·160	0·168	0·389	13·4	53·86	24·92	25·92
21 Top . .	1518	11	18	36	45	05	18	4·29	4·62	11·04	7·40	0·326	0·351	0·838	13·2	54·03	25·57	27·77
21 (38¾ cm.) .	1518	11	18	36	45	05	18	4·78	5·25	8·71	8·24	0·412	0·452	0·751	11·6	36·24	17·50	19·24
85 . .	1687	19	24	54	69	18	48	2·06	2·20	4·25	3·55	0·125	0·133	0·258	16·5	45·39	21·27	22·11
63 . .	1703	24	37	18	63	07	36	1·16	1·20	1·39	2·00	0·134	0·139	0·161	8·7	12·87	5·88	6·00
62 Top . .	1893	22	53	30	64	56	10	1·23	1·29	1·79	2·12	0·122	0·128	0·178	10·1	26·57	12·27	12·55
62 (20¾ cm.) .	1893	22	53	30	64	56	10	0·81	0·84	1·41	1·40	0·046	0·048	0·080	17·6	39·33	17·86	18·13
59 . .	1948	22	22	48	60	06	24	2·61	2·79	4·40	4·50	0·253	0·270	0·427	10·3	34·41	16·14	16·95

26 Top . .	2312	12	29	30	50	51	30	2·63	2·86	5·90	4·53	0·232	0·252	0·521	11·3	47·46	22·69	23·86
26 (30½ cm.) .	2312	12	29	30	50	51	30	1·59	1·69	5·06	2·74	0·119	0·126	0·379	13·4	62·90	29·33	30·21
26 (54½ cm.) .	2312	12	29	30	50	51	30	1·51	1·60	5·82	2·60	0·107	0·113	0·412	14·1	68·36	31·88	32·78
135 Top . .	2727	4	37	42 S.	72	35	36	0·93	0·98	7·40	1·60	0·034	0·036	0·271	27·4	82·58	38·17	38·83
135 (62¾ cm.) .	2727	4	37	42	72	35	36	1·04	1·10	3·49	1·79	0·054	0·057	0·181	19·3	64·80	30·13	30·71
135 (114¾ cm.).	2727	4	37	42	72	35	36	0·86	0·90	4·26	1·48	0·036	0·038	0·178	23·9	75·67	34·71	35·26
60 . .	3054	21	58	00 N.	62	19	42	0·70	0·72	1·09	1·21	0·052	0·054	0·081	13·5	32·84	14·86	15·05
76 . .	3289	24	10	36	59	00	36	1·24	1·29	1·47	2·14	0·140	0·145	0·166	9·0	12·05	5·50	5·62
81 . .	3351	23	17	06	61	00	36	1·22	1·28	1·46	2·10	0·155	0·163	0·185	7·9	11·62	5·37	5·49
170 . .	3676	7	38	48	58	18	30	0·56	0·58	3·72	0·97	0·026	0·027	0·173	21·5	81·60	37·12	37·50
92 . .	3722	16	09	36	68	50	54	1·29	1·34	3·26	2·22	0·055	0·057	0·139	23·5	57·03	25·94	26·56
93 Top . .	3991	14	24	24	66	12	42	0·71	0·74	2·00	1·22	0·045	0·047	0·127	15·8	60·64	27·75	28·10
93 (50 cm.) .	3991	14	24	24	66	12	42	0·57	0·59	0·93	0·98	0·039	0·040	0·063	14·6	34·97	15·95	16·12
93 (83¾ cm.) .	3991	14	24	24	66	12	42	0·67	0·72	0·97	1·16	0·052	0·056	0·075	12·9	24·24	11·39	11·53
167 Top . .	4042	7	11	48	63	05	36	0·45	0·47	1·74	0·78	0·034	0·036	0·132	13·2	69·85	32·10	32·36
167 (48¼ cm.) .	4042	7	11	48	63	05	36	0·31	0·32	0·98	0·53	0·026	0·027	0·082	11·9	64·21	29·43	29·60
167 (108¾ cm.).	4042	7	11	48	63	05	36	0·50	0·52	1·35	0·86	0·032	0·033	0·087	15·6	58·57	26·96	27·20
128 Top . .	4060	5	31	42 S.	49	33	30	1·01	1·07	3·98	1·74	0·039	0·041	0·154	25·9	68·69	32·10	32·71
128 (48¼ cm.) .	4060	5	31	42	49	33	30	0·78	0·82	4·87	1·35	0·022	0·023	0·137	35·5	79·47	36·60	37·13
128 (99 cm.) .	4060	5	31	42	49	33	30	0·59	0·63	2·51	1·02	0·023	0·024	0·098	25·7	70·46	32·98	33·34
132 Top . .	4082	1	01	24 N.	66	23	06	1·13	1·20	5·32	1·95	0·033	0·035	0·155	34·2	72·90	34·05	34·77
132 (48¾ cm.) .	4082	1	01	24	66	23	06	0·71	0·75	2·60	1·22	0·041	0·043	0·150	17·3	67·74	31·34	31·75
132 (114¼ cm.) .	4082	1	01	24	66	23	06	0·77	0·81	3·04	1·33	0·034	0·036	0·134	22·6	69·81	32·27	32·73
127 . .	4091	7	32	24 S.	44	09	30	0·70	0·75	2·21	1·21	0·032	0·034	0·101	21·9	62·20	29·14	29·52
134 Top . .	4234	2	55	30 N.	70	05	30	1·20	1·31	3·32	2·07	0·053	0·058	0·147	22·6	55·81	26·68	27·30
134 (107½ cm.) .	4234	2	55	30	70	05	30	0·75	0·81	1·85	1·29	0·034	0·037	0·084	22·1	52·61	24·84	25·19
134 (118 cm.) .	4234	2	55	30	70	05	30	0·63	0·67	1·51	1·09	0·035	0·037	0·084	18·0	51·94	24·41	24·69
101 Top .	4285	1	25	00	47	37	48	1·50	1·64	2·73	2·59	0·110	0·120	0·200	13·6	36·50	17·56	18·06
101 (32¼ cm.) .	4285	1	25	00	47	37	48	1·07	1·14	2·82	1·85	0·059	0·063	0·155	18·1	55·84	26·17	26·70
101 (88¼ cm.) .	4285	1	25	00	47	37	48	1·52	1·64	4·55	2·62	0·077	0·083	0·231	19·7	59·53	28·17	28·98
166 Top . .	4793	6	55	18	67	11	18	0·76	0·83	0·85	1·31	0·030	0·033	0·034	25·3	2·36	1·14	1·15
166 (22¼ cm.) .	4793	6	55	18	67	11	18	0·65	0·70	0·72	1·12	0·037	0·040	0·041	17·6	1·87	0·88	0·90
166 (50¼ cm.) .	4793	6	55	18	67	11	18	0·67	0·72	0·74	1·16	0·042	0·045	0·046	16·0	1·50	0·71	0·72
166 (76¼ cm.) .	4793	6	55	18	67	11	18	0·49	0·53	0·54	0·84	0·046	0·050	0·051	10·7	2·14	1·02	1·03
M 4932 . .	3154	24	20	50	59	24	40	0·56			0·97	0·115			4·9	17·47		
M 7644 . .	3694	17	38	30	59	04	00	1·62			2·79	0·113			14·3	52·53		
M 7645 . .	3292	17	17	00	57	34	00	3·09			5·33	0·303			10·2	50·86		

by bacteria when falling to the sea-bottom, where they may be ingested by animals, decomposed by bacteria, or deposited in the sediments.

The breakdown of proteinaceous organic matter in soils by bacteria and the oxidation of ammonia through the intermediary of nitrite to nitrate has long been known, but this theory was not applied to the oceans until the close of the last century. In the sea neither animal nor plant life can use gaseous nitrogen : plant life depends for its growth upon the nutrient salts. In the photosynthetic zone of the ocean phytoplankton transform the soluble forms of nitrogen into complex organic forms, and during this process liberate oxygen. When the plants die, as well as the animals which feed upon them, nitrogen is brought again into solution in the form of ammonia, through the action of bacteria, but before the nitrogen is again assimilated by marine plants ammonia is oxidized first to nitrite and then to nitrate by the action of certain other bacteria. It is commonly regarded by oceanographers that the cycle nitrate —→ plants —→ nitrate is a closed one, but the occurrence of organic matter in the lower portions of cores, as well as its occurrence in geological formations, indicates that a certain proportion of nitrogen and carbon of the organic matter is not regenerated.

The classical series of experiments done at the Plymouth Laboratory (Atkins, 1923 ; Harvey, 1926, 1928 ; Cooper, 1933) have shown that there is a cycle in the amount of nutrient salts present in the English Channel, which corresponds with the annual cycle of phytoplankton. In the winter months there is a storing up of nutrient salts owing, as Harvey has suggested, to the lack of light limiting the growth of phytoplankton, and in spring the rapid outburst is conditioned by the increased amount of sunlight. This is followed by a rapid fall in the amount of nutrients in the sea-water.

Brand (1937*b*) has clearly demonstrated the regeneration of nitrogenous organic matter in sea-water. Using a natural source of organic plankton he found that the rate of decomposition was greatest in the first few days. Ammonia appeared in the water immediately decomposition commenced, and it reached a maximum at the end of plankton decomposition. The gradual disappearance of ammonia was accompanied by the increasing amount of nitrite, which in turn was oxidized to nitrate. Nitrate reached its maximum concentration after nitrite had commenced to disappear, and the regenerated nitrate supported a rapid growth of diatoms when inoculated with a fresh culture.

(*b*) Physical and Chemical Factors.

By far the most important factor which governs the production of phytoplankton is light, since the illumination below the surface of the ocean, owing to absorption by the water and scattering by the particles suspended in it, falls off rapidly with depth. Temperature does not inhibit the production of phytoplankton, as diatoms occur over a very wide range, but the Coccolithophoridæ which are characteristic of tropical waters are never found in temperate regions. Temperature, as Gilson (1937*a*) remarks, has an important indirect effect on the production of plankton, as the density difference between the surface layer warmed by the sun and the cooler water below prevents mixing across the discontinuity layer, and so cuts off the possibility of the nutrient salts becoming available from the deeper waters.

Nitrates, phosphates and silicates are most important for plankton production, as it

is on the supply of these, provided there is sufficient light, that the productivity of an area depends. During the rapid growth of plankton the supply of nutrients is rapidly depleted, and if these are not renewed in the surface layers (the means by which this is done will be discussed later) plankton production rapidly ceases. Harvey (1928) observed that in the English Channel when the supply of nutrients diminishes phytoplankton production rapidly falls off, and the work of the "Discovery" Investigations indicates that there is generally in the Antarctic a sympathetic relation between the silica content and phytoplankton production. Iron is another essential element for plant growth, since it is required in the formation of chlorophyll. Unfortunately very little is known about the distribution of iron in the seas. Thompson (1935) found the iron content in the water beyond the continental shelf to vary between 12 to 54 mgrm. per cubic metre, and Cooper (1935) considers that not more than 2 mgrm. Fe per cubic metre is in true solution. Since the iron content of phytoplankton is approximately four times the phosphorus content, Cooper suggests that during an outburst the iron requirements must be very great. The occurrence of trihydrone molecules, especially in Arctic waters, may possibly influence the growth of phytoplankton. In this connection Barnes (1932) found that *Spirogyra* grows more rapidly in water that had been recently frozen than in recently distilled water.

It has previously been remarked that during active plankton production the available nutrients in the upper layers rapidly decrease, and consequently an understanding of the renewal processes is of obvious importance if any attempt is to be made to correlate the abundance of organic matter in sediments with areas which from hydrological considerations are suitable for the renewal of surface waters.

During a period of production the dead plankton sink and carry out of the illuminated zone the nutrient substances so essential to plankton growth. The renewal of the surface water with nutrients could be brought about by the regeneration of the nutrients in the dead plankton and a subsequent upward circulation of the water, or by the incoming of river water rich in nutrients, or possibly by the atmospheric fixation of nitrogen. But as Brandt (1902) has pointed out, the abundance of nitrate in the deeper layers suggests that nitrification takes place at the sea bottom or close to it; so to-day the alternative hypotheses find little support.

In stable water conditions nutrients remain largely concentrated in a stable bottom layer, and the question arises as to how this stability is upset. In winter in both Temperate and Arctic regions the upper layers of the sea rapidly cool and the density increases; consequently unstable conditions are set up, and helped by the wind and the tide the whole body of the water may, in shallow water regions, become homogeneous from top to bottom. The nutrients now occurring in the top layer cannot, owing to the absence of sufficient light, be used until the next spring. In certain regions of the world a continuous supply of nutrients is made available by the upwelling of bottom waters, and these regions are likely to be stocked with abundant plankton—a fact which was recognized by Nathansohn (1906). In the North Atlantic, for example, this occurs where deep water runs up shallow plateaux, or where submarine ridges cause bottom currents to be deflected, as in the neighbourhood of the Faeroes (Gran, 1929). Alternatively supplies of nutrients may be brought by upwelling, as demonstrated by McEwen (1916). The theory of upwelling depends on the fact that a body is only in equilibrium with the earth's surface when at rest, but when set in motion the effect of the earth's rotation is to deflect the direction of its motion to the right of the force in the northern hemisphere and to the left in the southern

hemisphere. Suppose, for example, the wind to blow uniformly and in a direction parallel to the coast in the northern hemisphere. If the coast is on the left of the wind the surface water would be carried away from the coast, and the surface water would be inclined upward away from the coast, and thus would give a pressure gradient towards the coast. If the depth exceeds twice the depth of frictional resistance the resultant current would, according to Ekman (1923), consist of three parts : a pure drift current at the top flowing to the right, a current in mid depths flowing parallel to the coast, and a bottom current flowing towards the coast, the flow of which must be equal to that of the upper current. Consequently upwelling of bottom water would result. Such a circulation exists, for example, off the Pacific Coast of North America (Michael, 1921) and accounts for the abnormally cold water characteristics of these regions, but the more recent work of Sverdrup (1938) suggests that the process is far more complicated than was assumed on the basis of earlier data.

VII. FACTORS GOVERNING THE ACCUMULATION OF ORGANIC MATTER.

It has recently been suggested by Seiwell (1938) that " organic particles (having a density not greater than that of the bottom water) sinking through water of variable density will approach some level asymptotically, and if organic debris in the sea should be sufficiently homogeneous, a stratum of maximum oxygen consumption may be conceived of as occurring in the sea " through the accumulations of decomposing organic particles at a certain level. This proposed biological explanation of the oxygen minimum layer is opposed to the theory of Dietrich (1936) and Wüst (1936). According to Seiwell's calculations at " Atlantis " station 1170, organic particles of radius 0·0885 cm. will approach asymptotically a level of about 600 metres in 400 hours, while particles of 0·708 cm. will approach a level of 1950 metres in 200 hours. Parr (1939*a*), in a recent paper, points out that Seiwell's asymptotic approach theory depends upon the assumption that the density of the particle (p) remains constant and only the density of the sea-water (p′) changes with depth, and at the asymptotic level (p–p′) = 0, and he suggests that no reasonable or even possible thermal expansion coefficient for such particles would permit organic particles to find equivalent densities in the sea-water, at which such particles would accumulate.

If an attempt is made to calculate the rate at which organic particles sink several difficulties are encountered, since any calculations must ultimately depend upon Stokes's law,

$$v = \frac{2.g\,r^2}{9\mu}(p-p'),$$

where v is the velocity of the settling particle of density p, r is its radius, and μ the viscosity of the sea-water of density p'. The formula stipulates that the particle should be spherical, but as this condition is obviously not fulfilled the term " equivalent radius " has been introduced by Odén. Further the particle will become smaller as decomposition proceeds, and the relation between $(p–p')$ and depth is completely unknown. Finally, although the viscosity of sea-water is known, and its variations with temperature and salinity (Krümmel, 1907), little is known of the effect of pressure.

Taking Seiwell's value 0·00242 for the difference of density between organic matter and sea-water, and assuming that this density difference remains constant (Parr, 1939*b*),

a particle of radius 0·1 cm. would take 17 days to sink at station 166 from 100 to 4793 metres. It has been assumed that since the effect of pressure on the viscosity of sea-water is unknown, the value of μ determined from the mean temperature and salinity of the water between 100 and 4793 metres is sufficiently accurate. If, however, the radius of the particle gradually decreases, the time taken to reach the bottom would be greatly increased, as the velocity of a falling particle is proportional to the square of the radius. Unfortunately, it is impossible to correct for this additional complication, as nothing is known about the size distribution of particulate matter in sea-water.

It is important to realize that even if the sea-bottom at one station contains more organic matter than at another, this does not necessarily imply that at the first station more organic material is deposited annually, as there may be relatively little inorganic matter deposited at the first place. In this connection Gripenberg (1934*d*) found that the late glacial muds of the Baltic contained less organic matter than the post-glacial, and suggested that this might be due to a decrease in the rate of sedimentation, though the increase in organic sedimentation may be partially due to the influence of the changing conditions at the commencement of post-glacial times. It is clear therefore that when attempting to correlate organic content of bottom sediments with the productivity of the sea, due consideration must be given to the possible variations introduced by differing rates of sedimentation.

As the density of particulate organic matter is approximately the same as that of sea-water, it is reasonable to expect organic matter to collect in regions characterized by mud deposits. One of the first to point this out was Boysen Jensen (1911*b*), who recorded high carbon contents from the muds of the Kattegat and low from the sands of the North Sea. This idea was further elaborated by Trask (1931*b*), who found a relation between the amount of organic matter and the submarine topography ; in the basins it is high and on the slopes it is lower. The grain size varies in a corresponding manner, being coarser on the ridge and finer in the basins. Whether this relation applies to regions away from the coast is unknown, and in our investigations insufficient mechanical analyses have yet been done to arrive at any definite conclusions.

A most important factor governing the accumulation of organic debris is biological activity, as much organic matter is consumed or regenerated long before it reaches the bottom. Brand (1937*a*, 1938) has reported that the amount of nitrogen in the particulate matter of sea-water varied from 0 to 47γ ($\gamma = 0{\cdot}001$ mgrm.) per litre. The greatest variations occurred in the upper 400 metres, and below this depth the amount is practically constant. It is suggested that these variations can be explained by differing living conditions in the two zones, as in the deeper layers conditions are practically uniform, resulting in relatively uniform and low nitrogen values owing to the absence of autotrophic organisms, apart from certain bacteria. The animals living in the deeper layers must depend for their food upon the remains and excreta of organisms living above, or possibly on bacteria (ZoBell, 1938), since Krogh (1934) has shown that dissolved organic nitrogen cannot be used appreciably by organisms. There is therefore an approach to a dynamic equilibrium, passing through many stages, between the particulate organic matter and living organisms. The excess organic matter is, of course, ultimately deposited in the sediments.

On the ocean floor a varied marine fauna, comprising representatives of all the major groups of marine animals, is present. At great depths complete darkness and very low

temperature retards the metabolism of the invertebrates, and it would seem that the number of individual animals living at great depths is very small.

In addition to the bottom-living animals, oceanic sediments support a large bacterial population. Certes (1884) found bacteria in all except four out of the 100 sediments collected at depths down to 5100 metres by the Talisman expedition, whilst Russell (1893) found 200 to 300,000 viable bacteria per c.cm. of bottom mud ; the overlying water seldom contained more than 100 per c.cm. Waksman and his collaborators at Woods Hole (1933) have demonstrated the presence of bacteria in sea muds capable of oxidizing ammonium salts to nitrite, but they found it more difficult to demonstrate the presence of nitrate-forming bacteria. In addition nitrate-reducing bacteria were found, but most of these organisms reduce nitrate to nitrite and not to atmospheric nitrogen. It is important to know to what extent bacteria are able to attack organic complexes present in bottom sediments, and how readily the nutrient salts can be regenerated and thus made available for plant synthesis. With this object in view Waksman and Hotchkiss (1938*a*) investigated the oxidation of organic matter in marine sediments by bacteria. Earlier experiments (Waksman, 1933*c*) indicated that dried mud, under purely artificial conditions, when remoistened was capable of giving off part of its carbon and a smaller amount of nitrogen, thus proving that the organic matter is not absolutely inert, but is capable of being slowly decomposed. In the later experiments the availability or stability of organic matter in marine sediments was measured by the oxygen consumption in sea-water. It was found that in fresh marine sediments the organic matter is oxidized very slowly by bacteria, which is very different from the rapid oxidation of planktonic material under similar conditions (Waksman, 1938*b*). In the period of the experiment (15–30 days) nitrites and nitrates could not be found in solution, and the oxidation process was found to take place at the expense of the non-nitrogenous organic complexes. Sediments recovered from considerable depths contain organic matter which oxidizes much less readily than that occurring in near shore deposits, indicating that organic matter in sediments from great depths is much more resistant than in sediments from shallow water.

The vertical distribution of bacteria in sediments off the Californian coast has been studied by ZoBell and Anderson (1936). The distribution of bacteria is independent of depth within limits of the observations (depths to 2000 metres), the temperature of the ocean floor and the distance from the mainland, but the bacterial content is greatly influenced by the organic content of the sediments. The upper parts of the cores contain the richest bacterial population, the numbers rapidly decreasing with depth. At the surface of the mud aerobes were more plentiful than anaerobes, but in the subsurface strata the reverse is the case. Cognizance should, however, be taken of the fact when interpreting the result that many bacteria are facultative anaerobes. In sea-water bacteria are most abundant in the surface layers, where usually a few hundred are present per c.cm. At depths below 200 metres very few bacteria can be demonstrated, whereas at the bottom the quantity ranges from several thousand to several million per wet gramme. The preponderance of bacteria in the sea-bottom has been attributed to several factors, such as more favourable oxidation-reduction conditions, to absorption by marine muds, to greater freedom from bacteria feeders, to the lower rate of metabolism owing to the lower temperatures, and to the concentration of organic matter. In bottom sediments as well as in oceanic waters a state of equilibrium exists between bacterial multiplication and bacterial destruction, and a change in this equilibrium may be brought about by a change in food supply,

environmental conditions, or a modification of agents unfavourable to bacteria. ZoBell agrees with Reuszer (1933) that the evidence at present indicates that the presence of utilizable organic matter is the most important single factor which influences the distribution of bacteria, but he indicates that the rate of multiplication of bacteria in sea-water is several thousand times as great as that in freshly collected bottom samples.

VIII. DISCUSSION AND INTERPRETATION OF RESULTS.

(*a*) Distribution of Organic Matter.

The distribution of organic matter in the sediments from the Arabian Sea is most readily appreciated by reference to Text-fig. 1, where the organic carbon content of the sediments is recorded on a H_2O– and NaCl free basis. Although a more extensive investigation would have been desirable, the present results suggest a large central area extending into the Gulf of Oman, where the carbon content of the sediments is smaller than 1%. Surrounding this is a belt containing 1 to 1·5%, and then a rich coastal area. In attempting to correlate these results with the distribution of nutrient salts, the authors have found the report published by Gilson (1937*b*) to be of the utmost value, but before commencing a description of the areas, the effects of the S.W. monsoon should be understood. From May to September the monsoon may cause considerable mixing in the upper layers of the ocean. When calm conditions are resumed in September considerable growth of phytoplankton is initiated, but owing to the shortage of nutrient salts this is mostly over by the end of January. From this time onward plankton is comparatively sparse except when upward water movements cause renewal of nutrient salts. The large outburst of diatoms recorded by Menon (1931) off the Madras coast has been correlated with the rains brought by the S.W. monsoon.

(*a*) *The Gulf of Aden.*

The amount of organic carbon found in the sediments from the Gulf of Aden is high, and varies between 2·21% at station 179 and 4·76% at station 20. According to Gilson the section from Aden to Berbera is characterized in the month of September by a sharp discontinuity layer. The warm surface water was depleted of nitrate and approached saturation with oxygen, and in the lower layer nitrite reached a high value below the density boundary, owing to the decay of plankton held up at this level. The deeper layers show a uniformly high nitrate concentration. At station 21 the upper twenty metres were in the month of October supersaturated with oxygen and practically depleted of nitrate. Immediately below the discontinuity layer nitrite reached its maximum. Approaching Cape Guardafui the stability is comparatively low and there is distinct evidence of turbulence. Unfortunately no quantitative plankton observations were made, but Gilson suggests that the low transparency of the water in the months of September and October indicates that the subsurface layers must have been rich in plankton. The low transparency cannot be attributed to material washed in from the land, as there are no rivers in this area.

When the expedition revisited the area in May warming of the sun had pushed the thermocline deeper, and plankton penetrating to the deeper layers through the less sharp discontinuity had carried the depletion of nitrate almost to the limit set by illumination.

In addition active plankton production was in progress as the supply of nutrients was no longer cut off by the steep and shallow thermocline.

The oceanographical observations suggest, therefore, a rich plankton-producing area, probably from October to May, and the organic carbon content of the bottom sediments confirms this conclusion.

(β) *The Arabian Coast.*

Upwelling occurs along this coast during the S.W. monsoon and consequently supplies of nutrients are brought to the surface. The expedition visited this area in October, and Gilson suggests that the oxygen, nitrite and transparency figures indicate that a period of considerable plankton production was coming to an end. The two samples investigated from this area, M7645 and M7644 (British Museum collections), contain respectively 3·09 and 1·62% of organic carbon on a H_2O–free basis. There is therefore a relation between the carbon content of the sediments and the plankton production.

(γ) *The Gulf of Oman.*

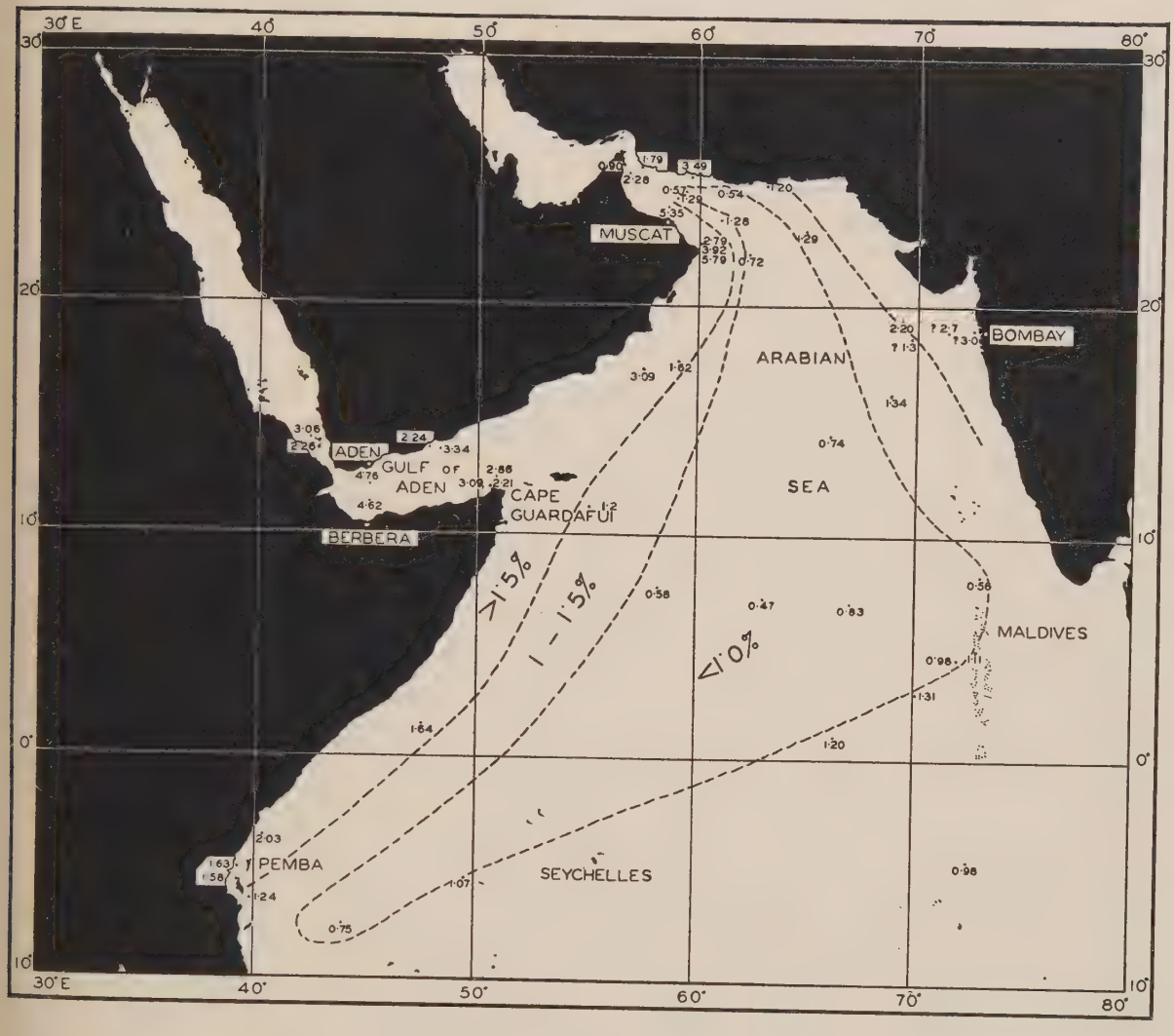
This area is characterized by low organic carbon in the centre, apparently connecting with the central area of the Arabian Sea. High organic carbon occurs along the coastal regions apart from one shallow water station 73. Unfortunately the oceanographical observations were taken in the month of November, so any outburst of plankton at the break-up of the S.W. monsoon would have been long past. It is interesting to note, however, that there is at about a depth of 150 metres on the Arabian side a tongue of low salinity water but rich in nitrate coming out of the Persian Gulf. The upper 30- to 40-metre layer is completely depleted of nutrient salts and consequently the oxygen figures are low. In a longitudinal section of the Gulf of Oman Gilson considers that there is little turbulence, and although the stability is not very high it is sufficient to prevent enrichment from the productive zone below. A correlation exists, therefore, between the sediments, moderately poor in organic carbon, from the central area and oceanographical considerations. The high carbon content of the coastal sediments would suggest however that at some period of the year there must be a considerable renewal of nutrients from below.

(δ) *The Arabian Sea.*

At station 85 2·20% organic carbon occurs, whilst Trask (1932*c*) has reported that the British Museum samples (M7631, M7624 and M7617) collected off Bombay contain 0·09, 0·19 and 0·21% nitrogen, corresponding to more than 1·5% of organic carbon. Proceeding into mid-oceanic waters only 0·74% of organic carbon occurs at station 93, whilst approaching the African coast organic carbon again increases, for a British Museum sample (M4302) S.E. of Socotra contains 0·08% of nitrogen (Trask, 1932*c*), corresponding to approximately 1·5% organic carbon. Along the African coast 1·64% organic carbon occurs at station 101, whilst at station 117, 2·03%. The sediments investigated from the Pemba Channel contain more than 1·5% organic carbon.

Matthews (1926) has demonstrated that during the S.W. monsoon season the northerly current along the African coast tends to move in a more easterly direction under the influence of the wind, and upwelling of deeper water results along the coast, and Gilson

states that at stations 100 and 101 there were still relics of this movement. The African coast is a rich plankton-producing area, and corresponding with this the sediments are rich in organic carbon. From Bombay as far as station 100, when the expedition visited this area in December to January, the surface layer was almost completely depleted of nutrient salts, and the area is probably a poor one in plankton production. This hypothesis agrees with the low carbon found at station 93, but the authors consider that the



TEXT-FIG. 1.—Distribution of organic carbon in the Arabian Sea.

increasing amounts of organic carbon found in the neighbourhood of Bombay would indicate at some period of the year an appreciable plankton production.

Along the most southerly section taken by the expedition low organic carbon occurs at station 127, 1% at station 128, 1·2% at station 132, and 1·3% at station 134. The present results would therefore suggest that in the southern portion of the Arabian Sea some of the sediments contain more than 1% organic carbon.

When the expedition visited this area in February to March the surface layer had a comparatively low stability, and mixing by the wind was very marked in the west, but as

the compensation level lay below the limit of such mixing it could cause no renewal in the supply of nutrients. In this connection it is interesting to recall the low organic carbon at station 127. Gilson considers that in the truly oceanic stations an outburst of plankton occurs at the end of the S.W. monsoon season, and that upwelling occurs on the lee side of the Seychelles Bank. The increased carbon content in the sediments may be correlated with these facts. At station 134 the low salinity surface water indicates an influx of water brought by the N.E. monsoon from the Bay of Bengal, Andaman Sea and the Malay region, and it has been suggested by Gilson that since enormous quantities of nitrate are brought down into the Bay of Bengal by the Ganges, this water may have a high nitrate content.

In the central section low amounts of organic carbon occur (ranging from 0·83% at station 166 to 0·47% at station 167), and this suggests that no very extensive plankton production takes place in this area. When the expedition visited this area in April, 1934, the transparency was high, but the utilization of the nutrients in the upper layer is incomplete, which may be due to the supply of nitrates being in excess of that of plankton production.

At station 169 on the Carlsberg Ridge Gilson reports abundant plankton and correlates this with the upward movement of the deep water. Unfortunately no bottom sample was collected, so it is impossible to say whether the rich plankton at this station affects the carbon content of the bottom sediments.

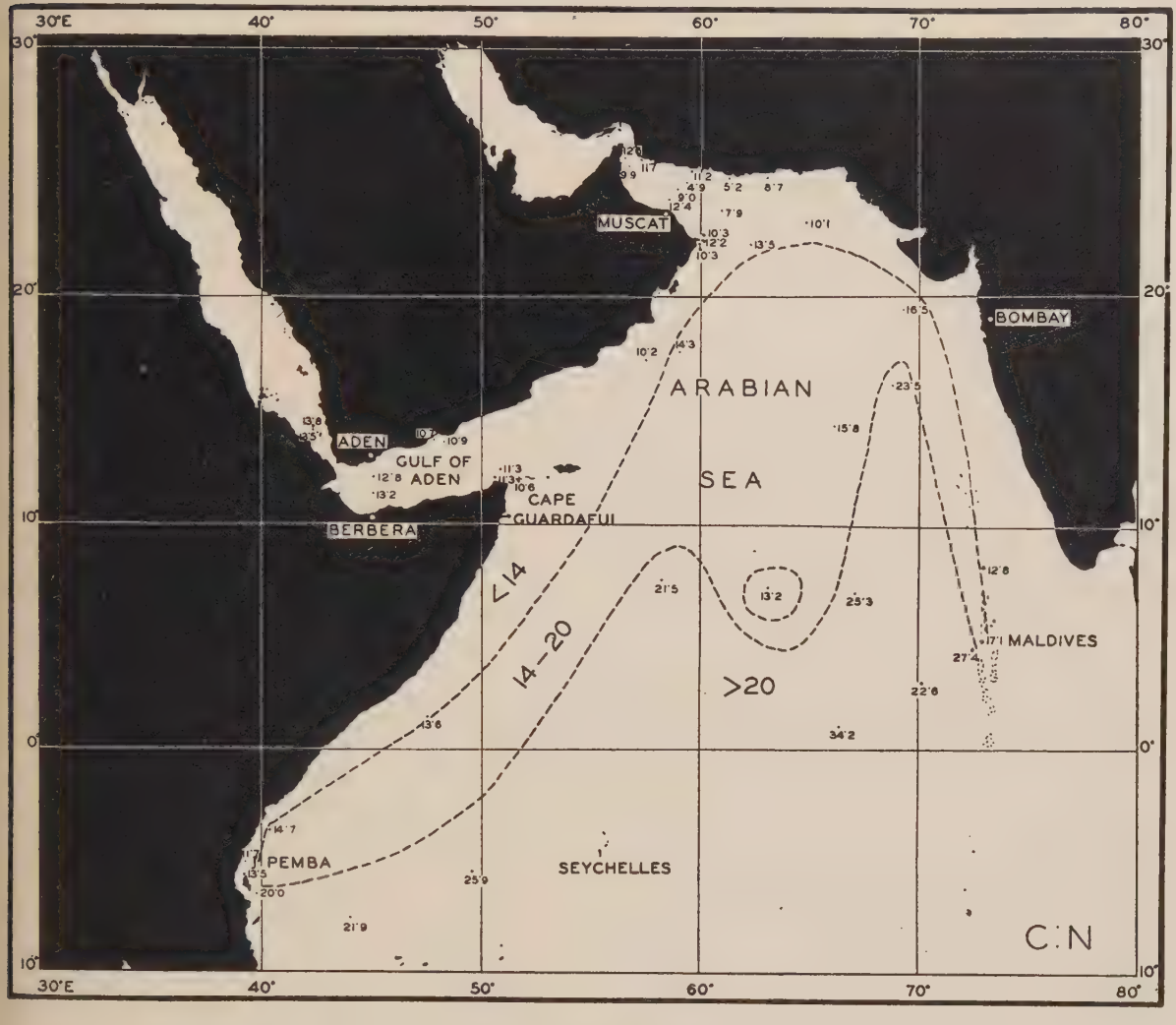
From the above results it may be said that in the Arabian Sea a connection exists between the productivity of the ocean and the organic carbon content of the sediments. The existence of such a relation should be of considerable use to those interested in the productivity of the oceans, and it would seem advisable for expeditions investigating the distribution of oceanic plankton to determine the organic carbon contents of marine deposits. The authors consider that interesting and corroborative evidence could be obtained by this method.

(*b*) The C : N Ratio in Surface Samples.

In the investigated sediments the C : N ratio varies between 4·9 and 34·2. Text-fig. 2, showing the distribution of the C : N ratio suggests, however, a tendency for regional constancy. In the Red Sea sediments from two neighbouring stations (207 and 206) have ratios 13·5 and 13·8 respectively, whilst the average of seven from the Gulf of Aden is 11·5, the ratio varying between 10·6 and 13·2. Along the Arabian Coast two samples have ratios 10·2 and 14·3 respectively, and in the Gulf of Oman the ratio varied between 4·9 and 13·5, the average for 15 different stations being 10·0. In the neighbourhood of the African coast, at station 101, C : N is 13·6 and 14·7 at station 117, whilst in the Pemba Channel two stations (114 and 106) have ratios 11·7 and 13·5, the average for the African coast being 13·4. At station 119, S.E. of Zanzibar, the C : N ratio is 20·0. This high value was rather unexpected, owing to its proximity to Africa, but similar values occur in the southern portion of the Arabian Sea. In eight selected oceanic stations values varied between 21·9 and 34·2, the average being 25·2. These high ratios are interesting, but it must be pointed out that this is not characteristic of all oceanic sediments, for stations 167 and 93 from the middle of the Arabian Sea have C : N ratios 13·2 and 15·8 respectively. Reviewing the available results, it may be concluded

that Arabian Sea coastal sediments have generally a C : N ratio smaller than 15, apart from station 119.

No obvious relation exists between the C : N ratio, depth or $CaCO_3$ content, nor is this ratio connected with the oxygen content of the bottom water. It might, however, be suggested that the lower ratios are due to the incoming of land organic debris, but this seems unlikely because low values occur in the middle of the Arabian Sea, and in addition



Text-fig. 2.—C : N ratio in sediments from the Arabian Sea.

the absence of large rivers capable of transporting appreciable quantities of land humus opposes such a hypothesis. Finally the lower ratios are not always maintained in the deeper portions of the cores. For example at station 101 the C : N ratio is 13·6 at the top and 19·7 in a deeper portion of the core, and again at station 62 the value at the top is 10·1 and 17·6 below. Conversely at station 132 the C : N ratio at the top is 34·2, whilst in a deeper portion it is 17·3.

Mention has previously been made of the variability of the C : N ratio in the Murray Samples, and of the errors introduced by calculating organic matter from the nitrogen

content. The basic idea underlying a relatively constant C : N ratio in marine sediments is organic matter of uniform composition, irrespective of locality and environmental conditions. Waksman (1929) has suggested that decomposition processes bring about an accumulation of resistant substances of plant origin and of nitrogenous substances of microbiological origin. As decomposition advances, the ratio of C : N in the product tends to become fairly constant, its value ranging from 8 to 12, the mean being 10.

The average C : N ratio for 108 sediments investigated by Trask (1932*d*) is 8·4, but in the Arabian Sea the average for 44 surface samples is 14·4, with variations from 4·9 to 34·2. The reason for the difference between these two averages is probably due to the sediments investigated by Trask coming from near shore environments. Similarly, Waksman's (1933*b*) conclusion that the C : N ratio of marine sediments is more or less constant is based on an inadequate study of deep-sea deposits. Gripenberg (1934*e*) found that the mean for Baltic sediments was 10·0, a ratio appreciably higher than that found by Trask. In the Baltic regional differences are found in the C : N ratio, the highest ratios occurring in the Bay of Bothnia. These variations are accounted for by the influence of land humus on organic sedimentation, the C : N ratio of humus from peat bogs being high. As plankton and animal life is poor in the Bay of Bothnia, the greatest effect is noticed here in spite of the fact of the moderately low addition of land humus.

A survey of the available results indicates that the idea of a constant C : N ratio for marine deposits originates through a study of deposits collected near the coast, and a further unwarranted application of this result to the uninvestigated oceanic regions. Our investigations, as previously mentioned, suggest that in the Arabian Sea coastal sediments have generally a ratio below 15, and that sediments farther out have a higher ratio, though exceptions, such as station 167, can be found to such a general rule.

The authors, although they cannot put forward a complete explanation for the reason of these apparent regional variations, suggest that it is largely due to some environmental conditions. That marine organic matter is not absolutely resistant to further decomposition by bacteria has been shown, as previously mentioned, by Waksman (1933*c*), who treated mud under purely artificial conditions and found a reduction in the C : N ratio. If a change in the C : N ratio can be brought about in laboratory experiments, it would seem unlikely that marine organic matter collecting on the bottom would be entirely uninfluenced by the surrounding conditions.

(*c*) Variations of Organic Carbon and Nitrogen with Depth in Sediment.

In order to determine whether there is a marked difference in the organic content of marine deposits at different ages, estimations were done on deeper portions of 16 cores. For convenience the results are collected in Table V. In seven cores the organic carbon (calculated on a H_2O- and NaCl free basis) decreases in the lower investigated portions, whilst in four cores organic carbon at first decreases and then increases. Three cores show an increase and then a decrease, whilst in the Red Clay core (station 166) a decrease, within the limits of experimental error occurs.

Nitrogen (recalculated without H_2O- and NaCl), apart from five cases, behaves sympathetically with organic carbon, but the C : N ratio does not, in general, remain constant in the lower portions of the cores. Organic carbon recalculated on a $CaCO_3$,

TABLE V.

Station No.	Organic carbon on a H_2O- and NaCl free basis.	Organic carbon on a $CaCO_3$, H_2O- and NaCl free basis.	Nitrogen on a H_2O- and NaCl free basis.	Nitrogen on a $CaCO_3$, H_2O- and NaCl free basis.
33 Top	3·34	6·80	0·306	0·622
33 (37½ cm.)	2·26	5·22	0·168	0·389
66 Top	5·35	8·26	0·432	0·667
66 (43 cm.)	4·62	6·99	0·306	0·463
20 Top	4·76	10·55	0·372	0·824
20 (41¼ cm.)	2·51	6·79	0·166	0·449
62 Top	1·29	1·79	0·128	0·178
62 (20¾ cm.)	0·84	1·41	0·048	0·080
26 Top	2·86	5·90	0·252	0·521
26 (30½ cm.)	1·69	5·06	0·126	0·379
26 (54½ cm.)	1·60	5·82	0·113	0·412
128 Top	1·07	3·98	0·041	0·154
128 (48¼ cm.)	0·82	4·87	0·023	0·137
128 (99 cm.)	0·63	2·51	0·024	0·098
134 Top	1·31	3·32	0·058	0·147
134 (107½ cm.)	0·81	1·85	0·037	0·084
134 (118 cm.)	0·67	1·51	0·037	0·084
21 Top	4·62	11·04	0·351	0·838
21 (38¾ cm.)	5·25	8·71	0·452	0·751
106 Top	1·58	4·76	0·117	0·352
106 (32¼ cm.)	1·65	4·95	0·121	0·365
106 (54½ cm.)	1·48	4·65	0·108	0·337
119 Top	1·24	3·13	0·062	0·157
119 (31¼ cm.)	1·89	2·99	0·123	0·195
119 (66¾ cm.)	1·14	2·83	0·059	0·145
135 Top	0·98	7·40	0·036	0·271
135 (62¾ cm.)	1·10	3·49	0·057	0·181
135 (114¾ cm.)	0·90	4·26	0·038	0·178
132 Top	1·20	5·32	0·035	0·155
132 (48¾ cm.)	0·75	2·60	0·043	0·150
132 (114¼ cm.)	0·81	3·04	0·036	0·134
101 Top	1·64	2·73	0·120	0·200
101 (32¼ cm.)	1·14	2·82	0·063	0·155
101 (88¼ cm.)	1·64	4·55	0·083	0·231
93 Top	0·74	2·00	0·047	0·127
93 (50 cm.)	0·59	0·93	0·040	0·063
93 (83¾ cm.)	0·72	0·97	0·056	0·075
167 Top	0·47	1·74	0·036	0·132
167 (48¼ cm.)	0·32	0·98	0·027	0·082
167 (108¾ cm.)	0·52	1·35	0·033	0·087
166 Top	0·83	0·85	0·033	0·034
166 (22¼ cm.)	0·70	0·72	0·040	0·041
166 (50¼ cm.)	0·72	0·74	0·045	0·046
166 (76¼ cm.)	0·53	0·54	0·050	0·051

H_2O- and NaCl free basis behaves in thirty-seven cases sympathetically with the organic carbon.

Comparing these results with the "Meteor" cores (Correns, 1937*a*) considerable agreement is noted, as Correns found that the organic carbon content sometimes decreases with depth, increases, or oscillates. Waksman (1933*b*) considers that there is generally a slow and gradual diminution in the amount of organic matter with depth, though in some cases the reverse holds, whilst Gripenberg (1934*f*) found that, to the depths reached by the sampler, late glacial clays had a uniform organic content, but post-glacial sediments decrease in organic matter in sediments from the Bay of Bothnia, but increase elsewhere. The content of organic matter at any depth in a core is a function of several factors, and does not solely depend on the productivity of the area when the sediment was deposited. It appears, however, that two factors may influence, in opposite directions, the organic content: the first being the decrease with depth caused by time of burial and biological considerations, the second being an increase with depth due to a decrease in the rate of sedimentation.

The rate of sedimentation is, in general, governed by two factors: firstly the amount of inorganic detritus (clay and other mineral particles) reaching the bottom, and secondly the amount of carbonate material, largely in the form of shells, arriving at the sea bottom. In many marine samples carbonate is greatly in excess of the clay and mineral components, and consequently a more accurate knowledge of the productivity may be obtained in such samples by calculating the organic carbon and nitrogen on a carbonate-free basis. The results of this recalculation are shown in the third and fifth columns of Table V.

(*d*) Variations of the C : N Ratio with Depth in Sediment.

The variations of the C : N ratio with depth and its relation to CO_2 content (recalculated without H_2O- and NaCl) are recorded in Table VI. From this table it is seen that an increase of the C : N ratio is accompanied by an increased CO_2 content, apart from the lower portion of station 66, and that a decrease of the C : N ratio is associated with a decreased CO_2 content in all cases except in the lowest portion of station 166. It is questionable whether the lower portion of the core at station 66 is really an exception, because the recalculated CO_2 figure is doubtful. (H_2O- was done at a later time and not on the same material.) In this connection it is significant to note that $CaCO_3$ uncorrected for H_2O- and NaCl has the following values: 31·11% in the upper portion and 31·34% in the lower portion.

Similarly the lowest portion of station 166 cannot rigorously be held as an exception; as the amounts of carbon and nitrogen are low, the limits of error could easily account for the discrepancy.

The top, middle and lower portions of the core from station 106 have practically the same CO_2 content, and corresponding with this the C : N ratio shows small variations. In some cores the C : N ratio oscillates, the middle portion having a lower or higher ratio than the top and bottom portions. In accordance with this behaviour the CO_2 content varies sympathetically, the only exception being the lowest portion of Station 167, and as the nitrogen is low, this can easily be accounted for by experimental error in the carbon or nitrogen determinations.

TABLE VI.

	Station No.	C : N.	CO_2.
Increase	62 Top	10·1	12·27
	62 (20¾ cm.)	18·7	17·86
	33 Top	10·9	22·37
	33 (37½ cm.)	13·4	24·92
	26 Top	11·3	22·69
	26 (30½ cm.)	13·4	29·33
	26 (54½ cm.)	14·1	31·88
	66 Top	12·4	15·48
	66 (43 cm.)	15·1	14·91
	20 Top	12·8	24·12
	20 (41¼ cm.)	15·1	27·70
	101 Top	13·6	17·56
	101 (32¼ cm.)	18·1	26·17
	101 (88¼ cm.)	19·7	28·17
Decrease	21 Top	13·2	25·57
	21 (38¾ cm.)	11·6	17·50
	93 Top	15·8	27·75
	93 (50 cm.)	14·6	15·95
	93 (83¾ cm.)	12·9	11·39
	134 Top	22·6	26·68
	134 (107½ cm.)	22·1	24·84
	134 (118 cm.)	18·0	24·41
	166 Top	25·3	1·14
	166 (22¼ cm.)	17·6	0·88
	166 (50¼ cm.)	16·0	0·71
	166 (76¼ cm.)	10·7	1·02
Approximately	106 Top	13·5	29·36
the same	106 (32¼ cm.)	13·6	29·34
	106 (54½ cm.)	13·8	29·93
Oscillate	167 Top	13·2	32·10
	167 (48¼ cm.)	11·9	29·43
	167 (108¾ cm.)	15·6	26·96
	119 Top	20·0	26·58
	119 (31¼ cm.)	15·4	16·19
	119 (66¾ cm.)	19·4	26·19
	128 Top	25·9	32·10
	128 (48¼ cm.)	35·5	36·60
	128 (99 cm.)	25·7	32·98
	135 Top	27·4	38·17
	135 (62¾ cm.)	19·3	30·13
	135 (114¾ cm.)	23·9	34·71
	132 Top	34·2	34·05
	132 (48¾ cm.)	17·3	31·34
	132 (88¼ cm.)	22·6	32·27

From these results it may tentatively be concluded that in the lower portions of the cores a sympathetic relation exists between the CO_2 content and the C : N ratio. The authors do not consider this relation as fortuitous, as estimations have been carried out at sixteen stations, nor would it seem likely that it is due to the limits of error in the organic carbon and nitrogen determinations. The possible experimental errors could alter appreciably the C : N ratio, especially when these substances occur in small amounts, but even with the maximum experimental errors occurring in the most favourable way no alteration of this relation occurs at five stations, whilst in general at the other stations the relation holds for two portions of the core and not for the third. It would seem unlikely that experimental errors acted suitably so as to give an artificial relation, especially as these possible exceptions only occur in samples poor in organic matter. Although there is, at present, sufficient evidence to suggest this relation, more determinations would have been desirable. The limitations of time, however, prevented more cores from being examined, and unfortunately no information is available in the literature. It would be unreasonable to expect this relation to hold for all oceanic deposits, but it should apply to those deposits in which there is a connection between the carbonate content and the physical and chemical properties of the bottom water.

In order to attempt a possible explanation it is necessary to point out the conditions which govern the solubility of $CaCO_3$ in sea-water. Johnston and Williamson (1916) demonstrated that the precipitation and solution of $CaCO_3$ in sea-water is governed by the law of mass action, $[Ca^{++}] \times [CO''_3] = K'_{CaCO_3}$, in which the brackets represent molar concentration, and K'_{CaCO_3} is the stochiometric solubility product in the presence of solid $CaCO_3$. From this equation it follows that under any conditions the solubility of $CaCO_3$ is controlled by the concentrations of calcium and carbonate ions and the value of the constant K'_{CaCO_3}. It is well known that salinity, temperature, hydrostatic pressure, CO_2 content and pH affect these factors, and it has been the task of several oceanographers to determine how these several factors affect the solubility.

The total concentration of calcium can be measured directly (Kirk, 1933), or its variations can be determined from the variations in the titratable base (Wattenberg, 1933), but the concentration of carbonate ions cannot be determined directly. It may, however, be calculated from the first and second dissociation constants of carbonic acid in sea-water, provided the pH is known. The first dissociation constant, at a salinity of $34^{\circ}/_{\circ\circ}$ and temperature of 20°, has a value of 10^{-6} (Buch, 1932), but the value of the second dissociation constant (Buch, 1930 ; Moberg, 1934) is more questionable. Further, as boric acid is present to the extent of about 18% of the titratable base, a correction for boron must be applied in order to determine the amount of the base which is balanced against carbonic acid. The first and second dissociation constants of $CaCO_3$ in sea-water vary with the salinity and temperature, but relations have been established between these factors. Finally, the effect of hydrostatic pressure on the dissociation constants of carbonic acid is unknown. Revelle (1934) has given a most useful table showing the comparative effects of changes in salinity, temperature and carbon dioxide content on the components of the system controlling the solubility of calcium carbonate. At saturation

$$\frac{[Ca^{++}] \times [CO''_3]}{K'_{CaCO_3}} = 1,$$

and in under-saturation solution this quotient is less than 1. According to Revelle at a

depth of 1000 metres (salinity 36°/$_{oo}$, temperature 5° C.) a change in the carbon dioxide content from 2·35 millimoles per litre to 2·40 per litre reduces the saturation quotient by −23%. He concludes that the most important factor controlling the solubility of $CaCO_3$ in sea-water is the CO_2 content, and the order of importance of the other physical constants is temperature, salinity and hydrostatic pressure.

In attempting to explain the possibility of the C : N ratio influencing the solubility of $CaCO_3$, it is first necessary to point out that the CO_2 content of sea-water is largely controlled by biological activity. If equilibrium conditions exist between the bottom water and sediment, a reduction of this ratio would increase the CO_2 content of the bottom water, and consequently the amount of carbonate in the sediment would decrease. With changing conditions it is possible, at a subsequent time, for the regeneration of organic carbon with reference to nitrogen to decrease (*i. e.* the C : N ratio increases). The CO_2 content of the bottom water would decrease and consequently the sediment would have an increased carbonate content. It is, therefore, possible to explain in the cores the apparent connection between the C : N ratio and carbonate content, but it is difficult to put forward any suggestion about the factors which favour the regeneration of organic carbon, as very little is known about the viability of bacteria in oceanic sediments and the conditions favouring the production of nitrifying or CO_2-producing bacteria. It would seem, therefore, impossible to suggest the conditions favourable to the development of certain specific bacteria until bacteriologists have made more detailed investigations about the bacteriological content of marine deposits.

Sediments with a comparable carbonate content are not always accompanied by the same C : N ratio, and in addition the rate of increase of the C : N ratio is not always the same as that of the carbonate content. These facts do not oppose the above-mentioned explanation, as the solubility of $CaCO_3$ depends not only on the CO_2 content, but also on temperature, salinity and hydrostatic pressure. In addition the rate of renewal of the bottom water must affect its CO_2 content, and the rate of accumulation of the non-carbonate components may influence the carbonate content of the sediment. It would, therefore, be unreasonable to expect all stations with the same C : N ratio to have the same carbonate content.

IX. SUMMARY AND CONCLUSIONS.

The amount of organic carbon and nitrogen has been determined on bottom sediments from 44 Arabian Sea Stations, and estimations have been made on the lower portions of 16 cores. In the Arabian Sea there is a large central area extending into the Gulf of Oman where the organic carbon content of the sediments is less than 1%. Surrounding this is a belt containing 1–1·5%, and then a coastal area with greater content. The distribution of organic carbon is in general agreement with the productivity of the area determined from chemical studies and plankton hauls.

The C : N ratio in surface samples varies between 4·9 and 34·2, though there is a tendency for a regional constancy of this ratio ; the average ratio for surface samples is 14·4. Previously it has been suggested by some investigators that, as a routine procedure, the estimations of organic matter can be most satisfactorily obtained from nitrogen, but the authors consider that this is likely to lead to very inaccurate results because of the variability of the C : N ratio.

In the lower portions of the investigated cores organic carbon and nitrogen may decrease, increase, or oscillate. The variations of the C : N ratio in the lower portions agree, in general, with the variations of the $CaCO_3$ content, and a provisional explanation for this is suggested. It is, in conclusion, to be hoped that future expeditions studying the productivity of the oceans will not ignore the information which may be obtained from the sediments, and will collect bottom samples with all possible oceanographical data. By this means more useful results will be obtained, which will be helpful in the interpretation of other problems.

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